

Ocean-atmosphere coupled mesoscale model simulations of precipitation in the Central Andes

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The meridional extent and complex orography of the South American continent contributes to a wide diversity of climate regimes ranging from hyper-arid deserts to tropical rainforests to sub-polar highland regions. In addition, South American meteorology and climate are also made further complicated by ENSO, a powerful coupled ocean-atmosphere phenomenon. Modelling studies in this region have typically resorted to either atmospheric mesoscale or atmosphere-ocean coupled global climate models. The latter offers full physics and high spatial resolution, but it is computationally inefficient typically lack an interactive ocean, whereas the former offers high computational efficiency and ocean-atmosphere coupling, but it lacks adequate spatial and temporal resolution to adequately resolve the complex orography and explicitly simulate precipitation. Explicit simulation of precipitation is vital in the Central Andes where rainfall rates are light ($0.5\text{-}5\text{ mm hr}^{-1}$), there is strong seasonality, and most precipitation is associated with weak mesoscale-organized convection. Recent increases in both computational power and model development have led to the advent of coupled ocean-atmosphere mesoscale models for both weather and climate study applications. These modelling systems, while computationally expensive, include two-way ocean-atmosphere coupling, high resolution, and explicit simulation of precipitation. In this study, we use the Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST), a fully-coupled mesoscale atmosphere-ocean modeling system. Previous work has shown COAWST to reasonably simulate the entire 2003-2004 wet season (Dec-Feb) as validated against both satellite and model analysis data when ECMWF interim analysis data were used for boundary conditions on a $27\text{-}9\text{-km}$ grid configuration (Outer grid extent: 60.4°S to 17.7°N and 118.6°W to 17.4°W).

We now evaluate COAWST model simulations using MIROC5 CMIP5 model for both its input and boundary conditions for an entire year (October 2003 – October 2004) and will evaluate its ability to simulate both seasonal precipitation patterns and weak mesoscale-organized convection in the Central Andes. Model validation will compare COAWST model output against ECMWF-interim analysis and the TRMM 3B42 precipitation product. To elucidate the impact of two-way ocean coupling, another simulation featuring one way feedback (ocean to atmosphere) was also completed. Both simulations successfully reproduced the seasonal cycle of precipitation in the Central Andes and in the Western Amazon and reproduced most of the key features that characterize the South American climate (i.e., Bolivian High, Argentinian Low, low-level jet, etc.). Precipitation associated with the monsoon trough however tended to be too weak due to an overabundance of upwelling along the equatorial zone, especially in the two-way coupled simulation where SSTs were up to 4K colder than in ECMWF-interim analysis. Unlike in Northeastern Brazil, COAWST simulations produced reasonable estimates of overall accumulated precipitation (as compared to TRMM) and also for the diurnal and seasonal cycles in the Central Andes. Accurate simulations in the Central Andes indicate COAWST did likely reproduce the key Rossby Wave response between strong convection in the Western Amazon and the strength of the Bolivian High which is a key moisture

transport mechanism for the Central Andes. When evaluated at particular points throughout the Central Andes, COAWST simulated precipitation days (days with > 5 mm/day) generally was within 30 days of that shown in TRMM 3B42. Finally, probability and cumulative distribution functions of precipitation over Tropical South America demonstrates COAWST simulated precipitation during the wet season was generally too light, but over higher terrain regions including the Central Andes rainfall histograms more closely resembled TRMM and was likely associated with more accurate simulations of orographically-forced precipitation.

Ocean-Atmosphere Coupled Model Simulations of Precipitation in the Central Andes

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Motivations and Objectives

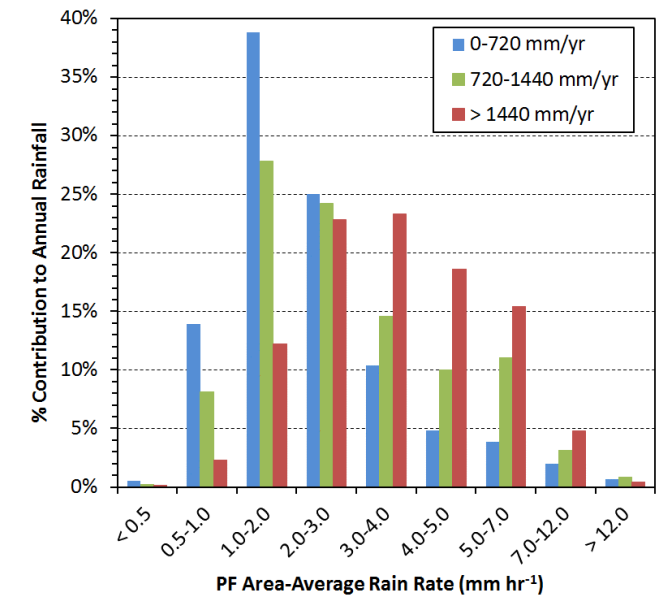
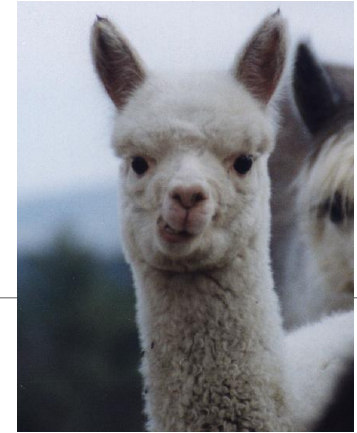
Precipitation climate: Diurnal cycle, total rainfall, distribution

Motivation:

- GCMs and CORDEX lack temporal and spatial resolution.
- Central Andes very sensitive to climate change
- Precipitation characterized by shallow convection, strong seasonal and regional dependence, and light rainfall rates (see right)

Objectives:

- Determine stability and feasibility of regional climate models (RCM) in climate-scale applications
- Run year-long RCM simulation to gain precipitation climate “snapshots”



TRMM PF rain rates as a function of percent contribution to annual rainfall in the Central Andes (mm) -- Figure from Karen I. Mohr

COAWST

Coupled Ocean-Atmosphere-Wave-Sedimentation Transport Model (COAWST)

4 model components

- Atmosphere (WRF), ocean (ROMS), wave (SWAN) sedimentation (CSTMS)

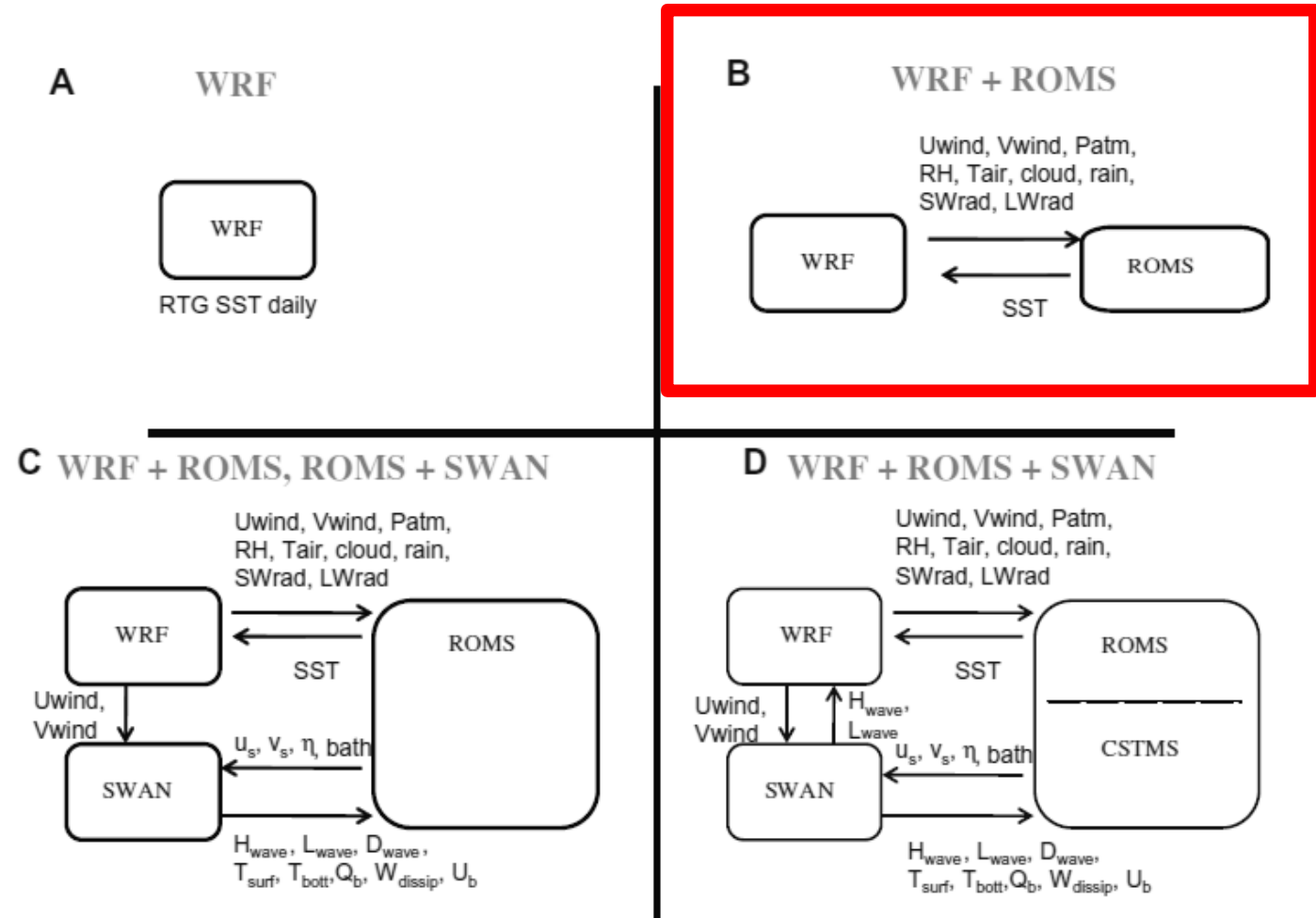
Only 1 coupled domain used

Multi-domain nesting added August 2014 (too late for this work!)

Will focus on WRF-ROMS coupling only

- Coarse resolutions (9km +)
- Long time scales (1 year)

Discrete, user specified data exchanges via model coupling toolkit and SCRIP



Adapted from Figure 5 from Warner et al. (2010)

Coupled model configuration

WRF – 2 model grids (27, 9 km)

- 61 vertical levels, 50 hPa model top
- ECMWF/CMIP5 input
- Time step 45 sec, 15 sec

ROMS – 1 model grid (10 km)

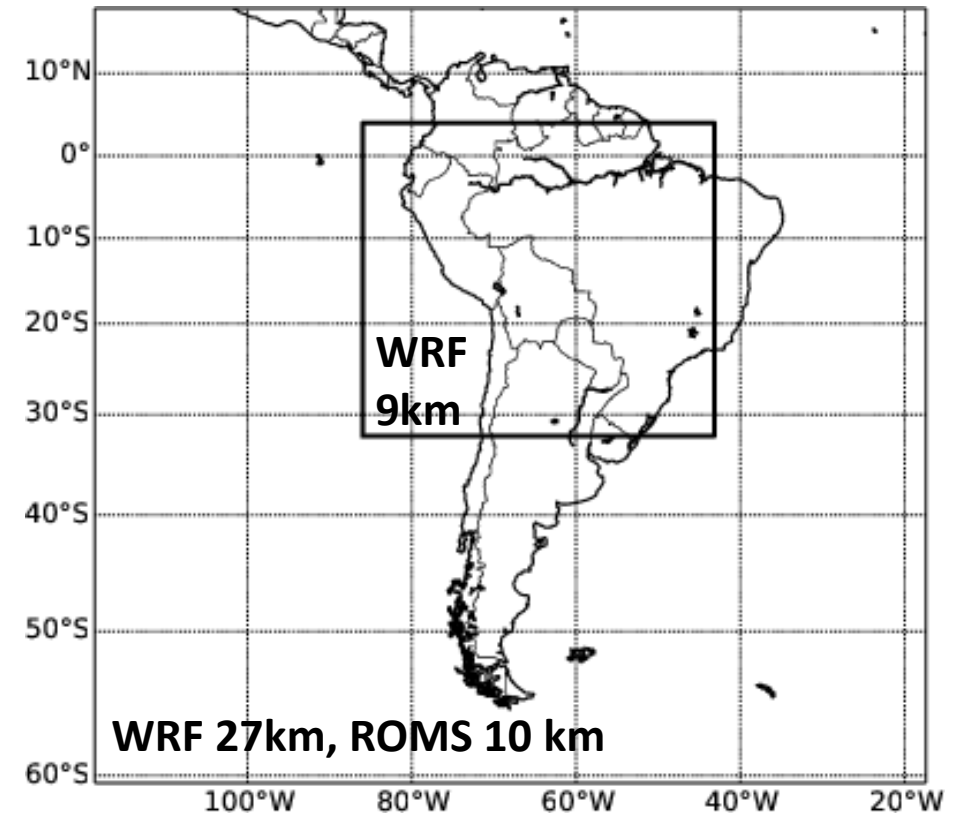
- 16 vertical levels, open boundaries
- ECMWF/CMIP5 input
- Time step 10 sec

Coupling once every 30 mins

Consider: Landuse, Convective parametrization, CMIP5, GHG

Due to computational/storage limits, restricted to 1-year (Oct – Oct) simulations for four different “snapshot” years:

- Goal: 2003 and later future years



Recent climate (1) – Overview

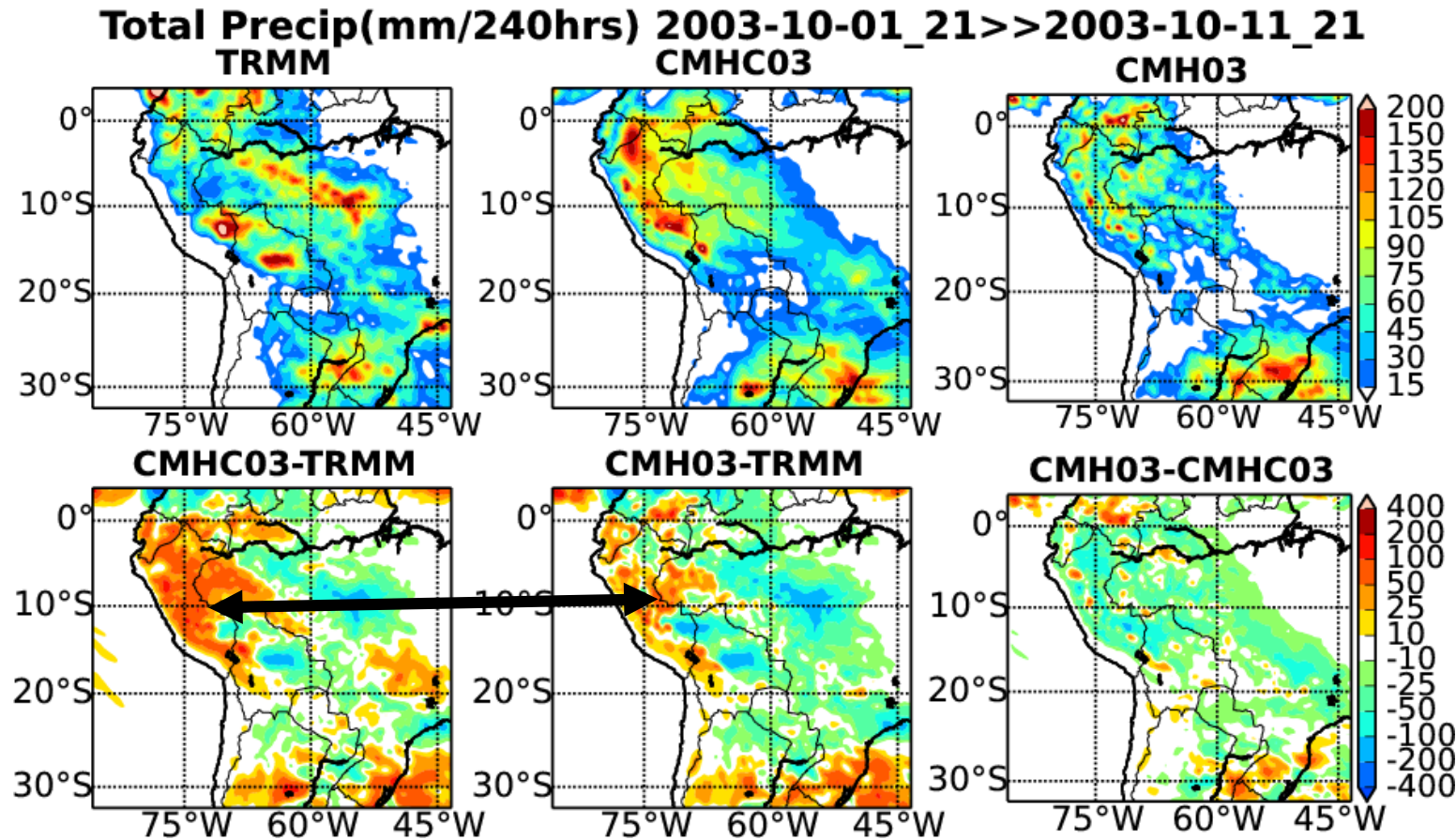
Model:

- Historical climate scenario (1850-2005)
- Simulations (Oct to Oct, i.e., the cover the entire wet season):
 - **WMH03** – Uncoupled WRF simulation using MIROC5 historical input, SSTs updated with MIROC5 SSTs
 - **CMH03** – Coupled WRF-ROMS simulation using MIROC5 historical input
 - **CGH03** – Coupled WRF-ROMS simulation using GFDL-ESM2M historical input
 - **CCH03** – Coupled WRF-ROMS simulation using CCSM4 historical input
- 2003 reference year; ENSO neutral

Validation:

- Tropical Rainfall Measuring Mission (TRMM) 3B42 daily precipitation product
- European Centre for Medium-Range Weather Forecasts Interim Analysis

Recent climate (2) - Convective parameterization

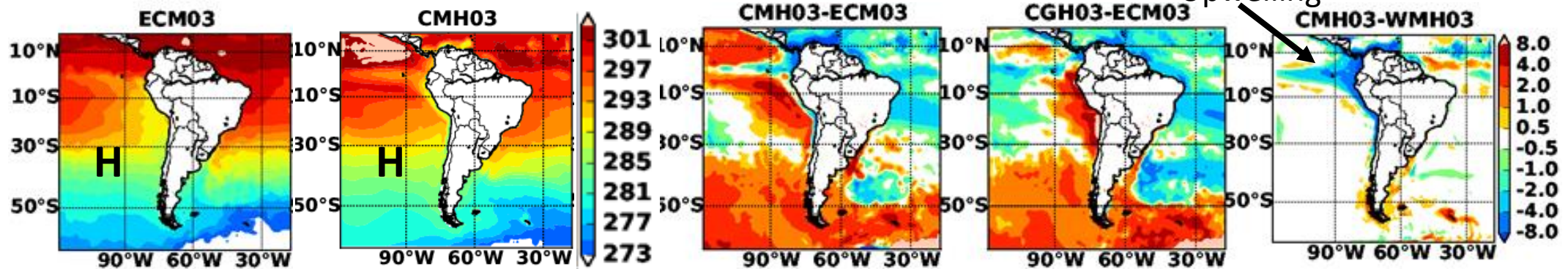


- Total precipitation (mm) 1 Oct – 11 Oct 2003
- Validation (top left): Tropical Rainfall Measuring Mission
- Kain-Fritsch:
 - Active: CMHC03
 - Inactive: CMH03
- Precipitation totals reduced without parameterization but more accurate totals

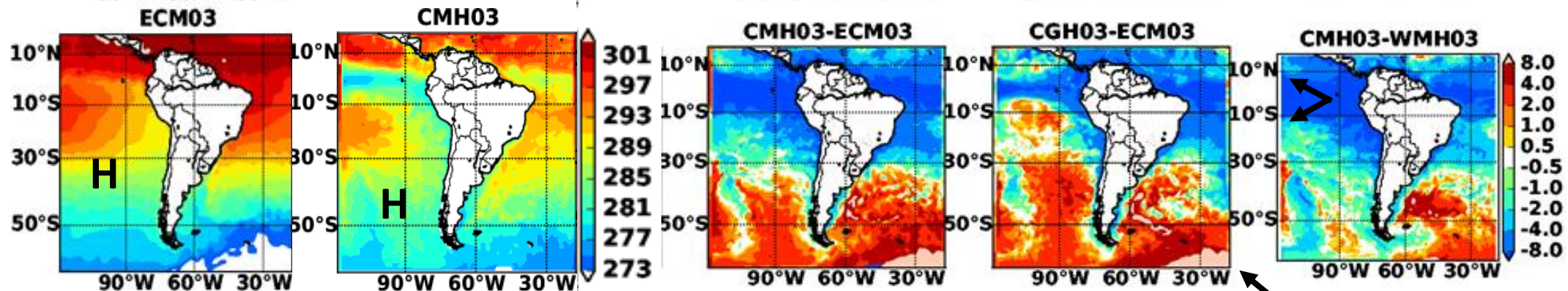
Recent climate (3) – 10-Averaged SSTs (K)

Upwelling

10/1-10/11/2003



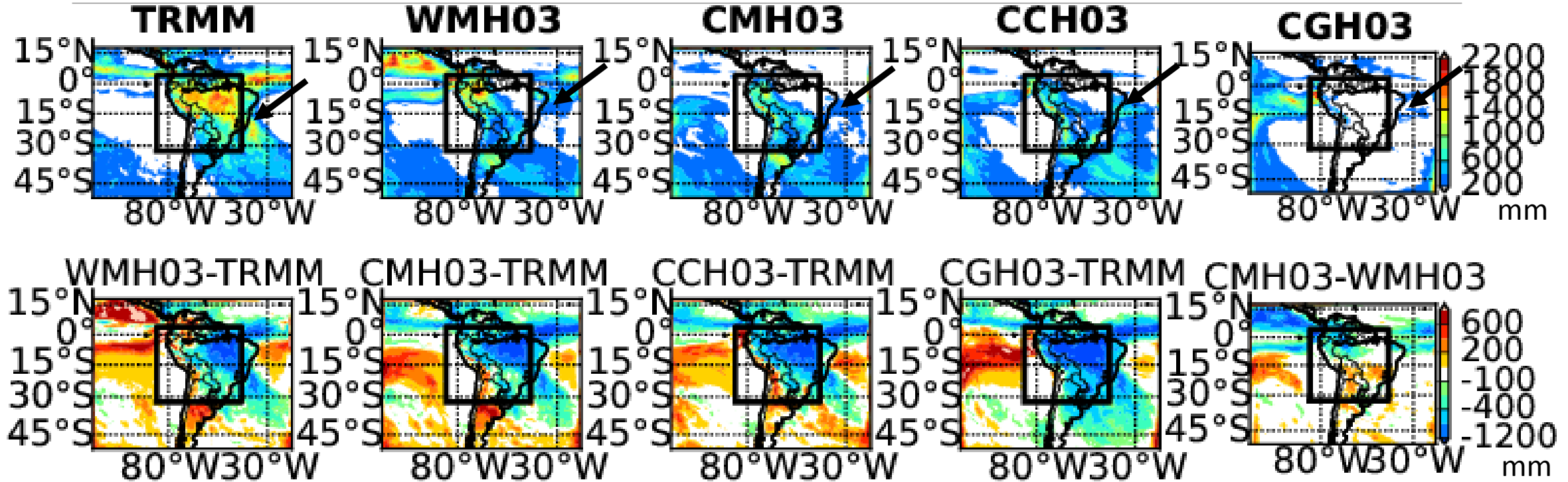
9/15-9/25/2004



- Initial SST differences (CMIP5 vs ECMWF)
- Upwelling along shallow mixed layer equatorial zone (Div)

- Inconsistency between atmosphere and ocean domains
- Warming poleward of 30°S (LBC, downwelling)
 - Weaker, more southward subtropical gyre

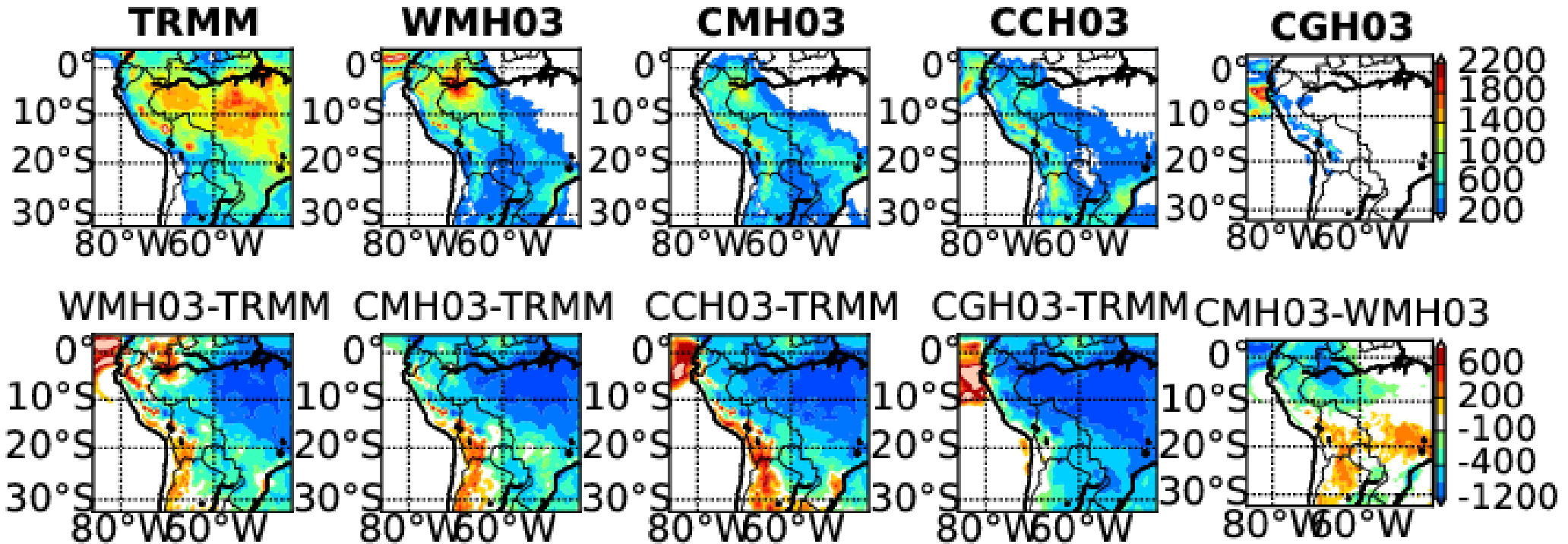
Recent climate (4) – Seasonal Precipitation – 27 km (1 Nov – 31 Mar)



- Upwelling in Equatorial regions kills convection (source: shallow mixed layer)
- Kept in place by shifted ITCZ (Pacific), on-shore flow (Atlantic)
- SACZ still present, but shifted northward (all exc. GFDL)
- Enhanced rainfall over warm water pockets (esp. GFDL), southward sub-tropical gyres

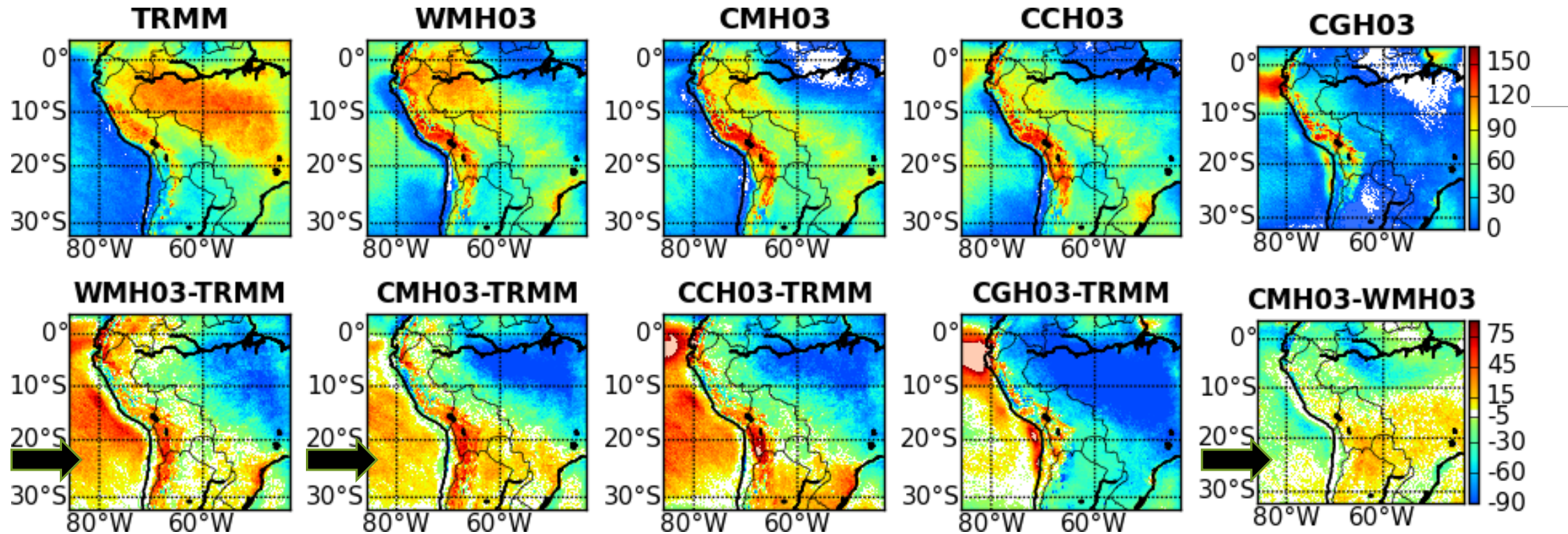
Recent climate (5) – Seasonal Precipitation – 9 km (1 Nov – 31 Mar)

Total Precip(mm/3624hrs) 2003-11-01_21>>2004-03-31_21



- At start: Land cool, E. Pacific warm
- N.E. South America dry bias (Cool SSTs, on-shore wind)
- W. Amazon warm spot (MIROC, CCSM, no GFDL)
- Altiplano (CCSM, MIROC)
 - Weaker, but more southward Bolivian High, higher θ_e
- Coupling: ↓ precip, closer to TRMM (Exc. Amazon)

Recent climate (6) – Precipitation Days



Nov 1 - Mar 31 Precip Days (152 days total)

| | TRMM | WMH03 | CMH03 | CCH03 | CGH03 |
|--------|------|------------|------------|------------|-------|
| Tuni | 120 | 105 | 132 | 110 | 96 |
| Sajama | 71 | 106 | 117 | 128 | 83 |
| Sucre | 89 | 119 | 127 | 102 | 84 |
| Cuzco | 118 | 117 | 118 | 91 | 107 |

Note: Bold = 20+ day difference from TRMM

○ Days > 0.05 mm (1 Nov – 31 Mar)

○ Consistent with precipitation

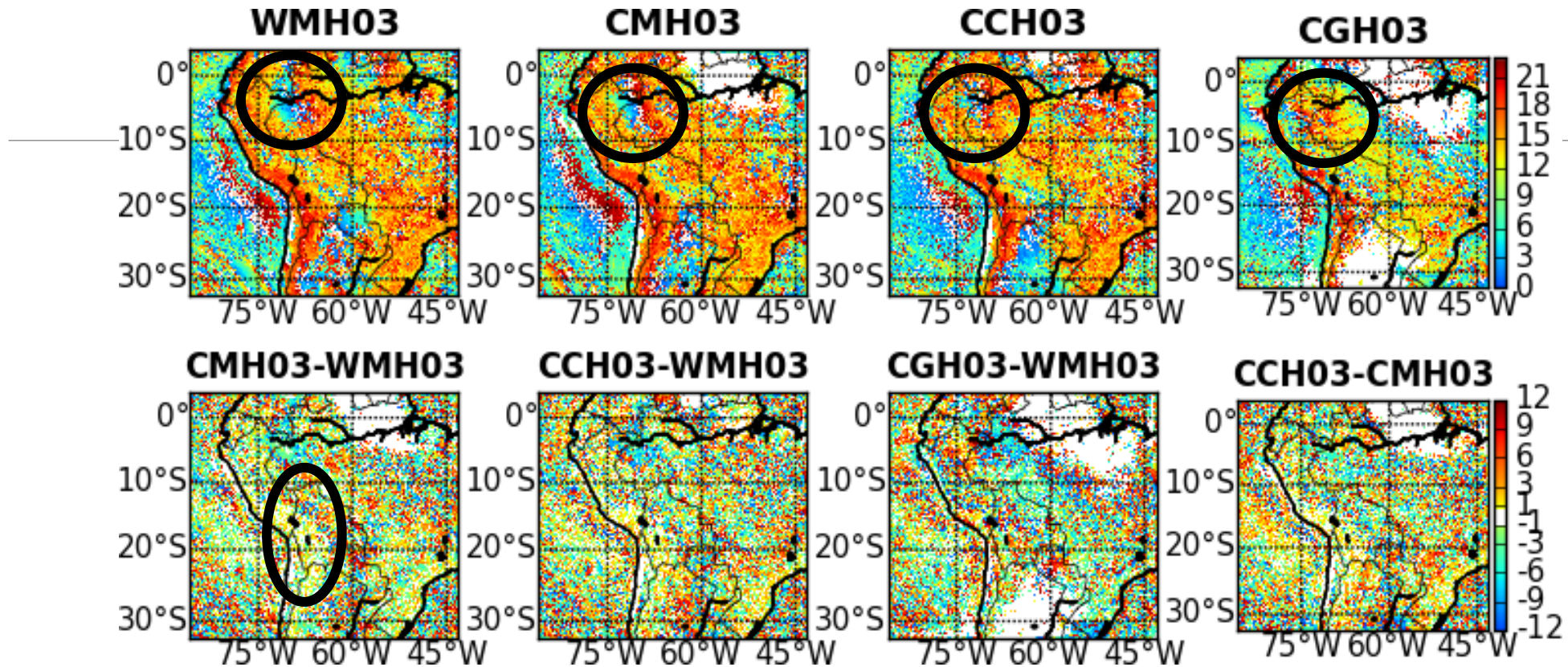
○ Coupled vs uncoupled -- Arrows

○ CGH03: Under predict (20 - 30°S)

○ Altiplano: Tendency for excess rain (57, Sajama)

○ TRMM bias

Recent climate (7) – Diurnal Precip Max



- Time of max daily precip (local time)
- Land >> WMH03, CMH03, CCH03 (+/- 2 hrs), GFDL (6-8 hrs) variations
- Oceans >> Consistent, all models
- Altiplano: Daily max (18-21 UTC), GFDL (15-18 UTC) – Bolivian High, Amazon
- Coupling: Little impact associated to with coupling (Oval)

Recent climate (8) – Diurnal Cycle

Diurnal cycle of precipitation (1 Nov – 31 Mar)

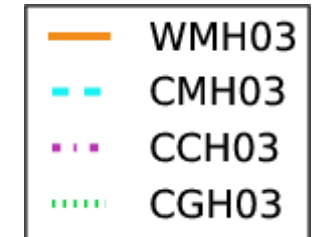
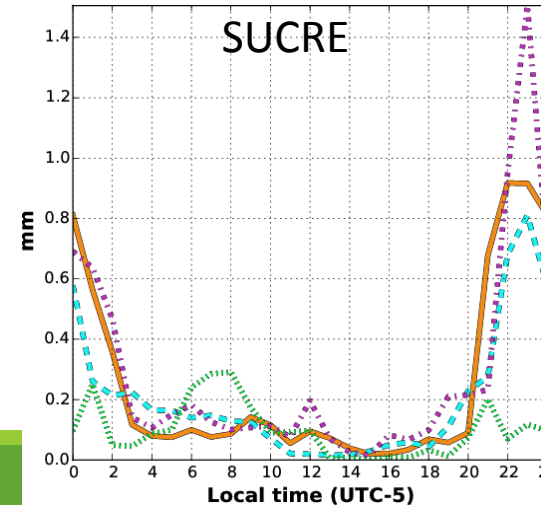
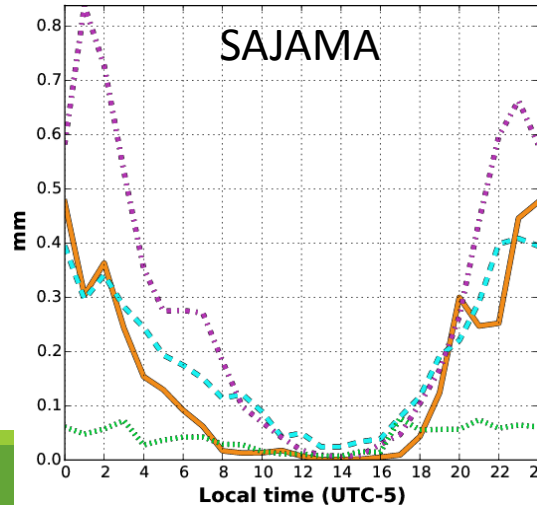
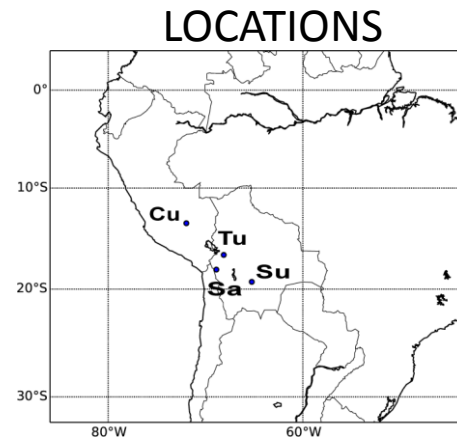
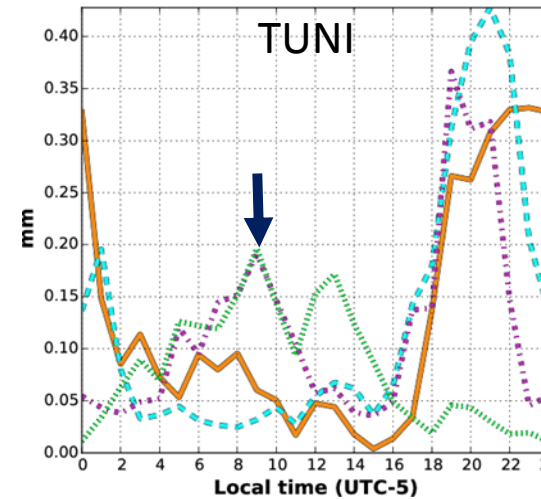
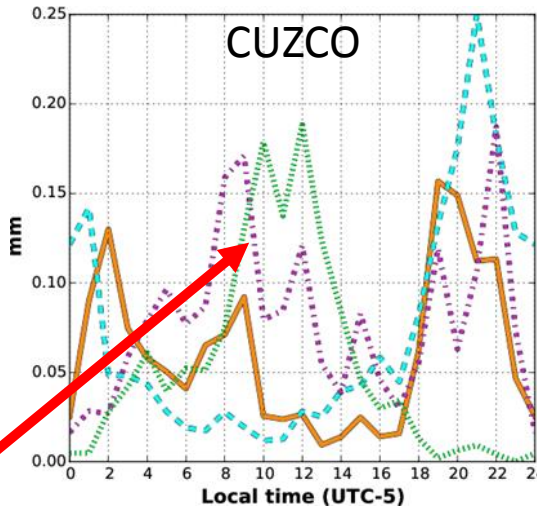
4 Altiplano regions (Western, Eastern, etc)

Regional variability within Altiplano given topographical differences

Timing of diurnal cycle is consistent for MIROC and CCSM (exc. Cuzco)

GFDL magnitudes shifted off other models 8-10 hours (blue arrows)

- Often ½ of less other models (blue arrows)
- Reason: Weaker Bolivian High



Summary

- Year-long (Oct–Oct) coupled, RCM (i.e., COAWST) simulations
 - MIROC5, CCSM4, GFDL-ESM2M input
- MIROC5 and CCSM simulations successfully developed main climate features (i.e., Bolivian High, Argentinean Low, diurnal cycle of Amazon convection, etc.)
 - Exception GFDL – Upper and mid-levels not initialized with decent accuracy
 - Other models: Not perfect, but decently accurate (expected vs ECMWF)
- Precipitation climate
 - Precipitation day surplus (15+ days), GFDL most accurate (not right reason)
 - Diurnal cycle well represented (MIROC, CCSM), but not by GFDL

Thank you for your
time!!!

Any questions????



Extras

WRF Parameterizations

- Microphysics – Goddard
- Longwave Rad. – New Goddard
- Shortwave Rad. – New Goddard
- Surface layer – Eta similarity
- Land Surface – NOAH
- Boundary Layer – Mellor-Yamada-Janjic
- Cumulus – Kain Fritsch (Turned off domain 2)

ROMS Parameterizations

```
#define ROMS_MODEL
# define WRF_MODEL
# define MCT_INTERP_OC2AT
#define UV_ADV
#define UV_COR
#define UV_VIS2
#define MIX_S_UV
#define TS_U3HADVECTION
#define TS_C4VADVECTION
#undef TS_MPDATA
# define UV_LOGDRAG
#define DJ_GRADPS
#define TS_DIF2
#define MIX_GEO_TS
#define SALINITY
#define SOLVE3D
#define SPLINES
#undef AVERAGES
#define NONLIN_EOS
#define MASKING
```

```
#define MCT_LIB
# undef BULK_FLUXES
# define ATM2OCN_FLUXES
# define ANA_SSFLUX
# undef LONGWAVE_OUT
#undef MY25_MIXING
# define KANTHA_CLAYSON
# define N2S2_HORAVG
#define RADIATION_2D /* ok */
#define RAMP_TIDES /* ok */
#define SSH_TIDES /* ok */
#define ADD_FSOBC /* ok */
#define ANA_FSOBC /* ok */
#define UV_TIDES /* ok */
#define ADD_M2OBC /* ok */
#define ANA_M2OBC /* ok */
#define EAST_FSCHAPMAN
#define EAST_M2FLATHER
#define EAST_M3RADIATION
#define EAST_TRADIATION /*
```

On-going and Future Work

3rd CMIP5 model: CCSM4

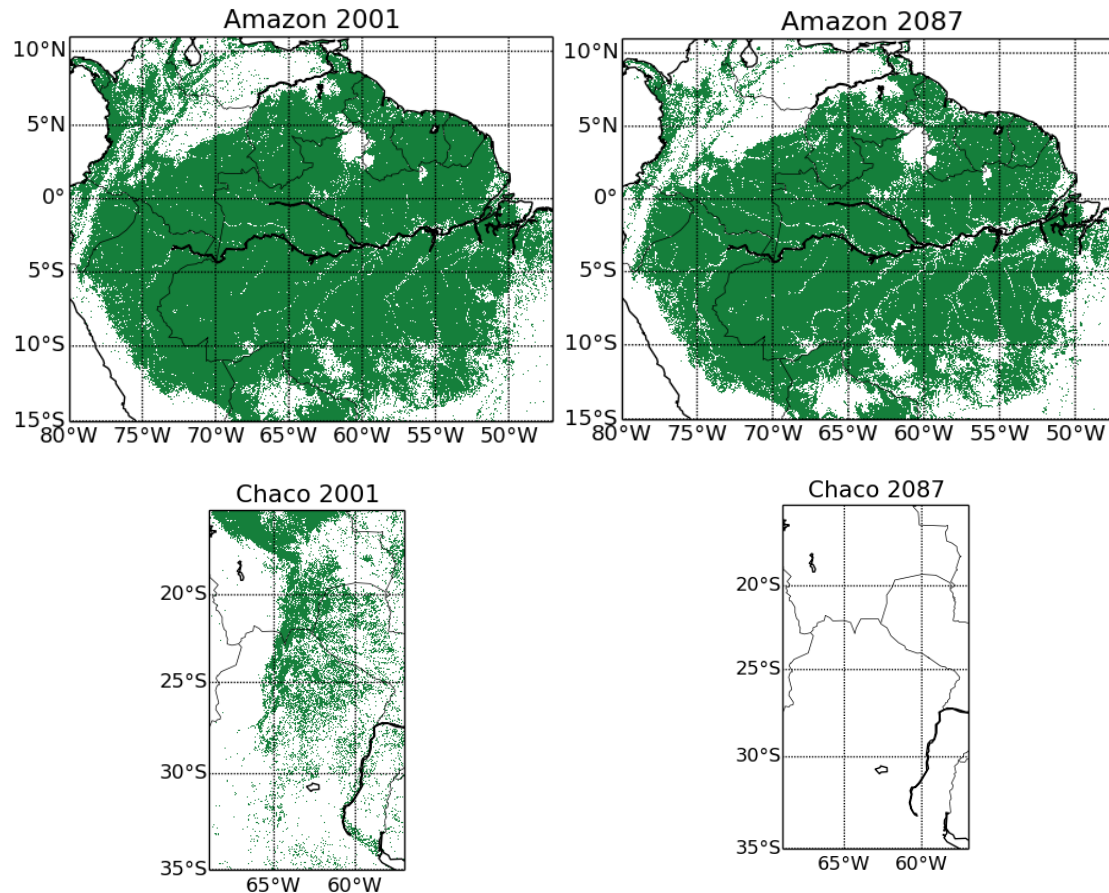
- Initial results: Precipitation patterns consistent with MIROC5, not GFDL

Re-runs – To address a couple raised concerns

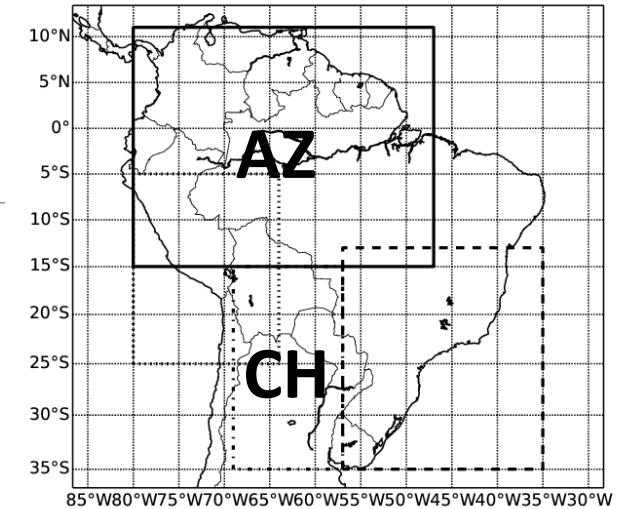
- Raising of model top to 10 hPa: Stratospheric circulations
- Applying fix for SST coupling in COAWST
- More accurate representations of GHG values from RCP 6.0 and other scenarios
- Run a second set of RCP 4.5 and RCP 8.5 simulations in 2087

Additional Considerations (1)

Biospheric Changes



Biospheric Regions



Amazon (AZ): Used Insitituto Nacional de Pesquisas Espaciais (INPE) data prior for 2013 and earlier then assumed 7,000 km² removed per year (Davidson et al 2012)

- 13.48% reduction by 2087 (787,392 km²)

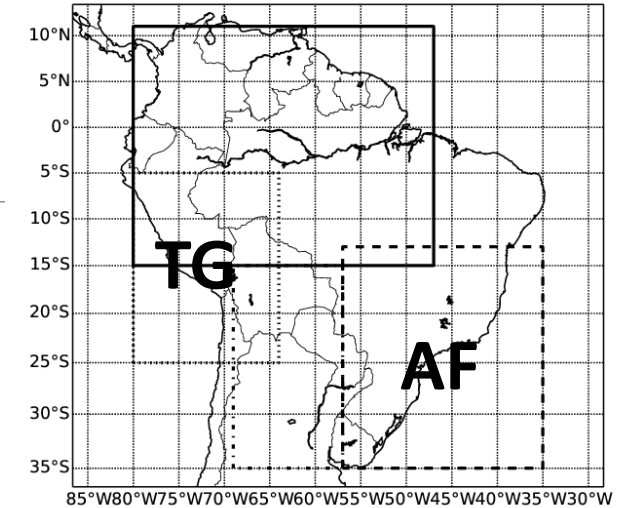
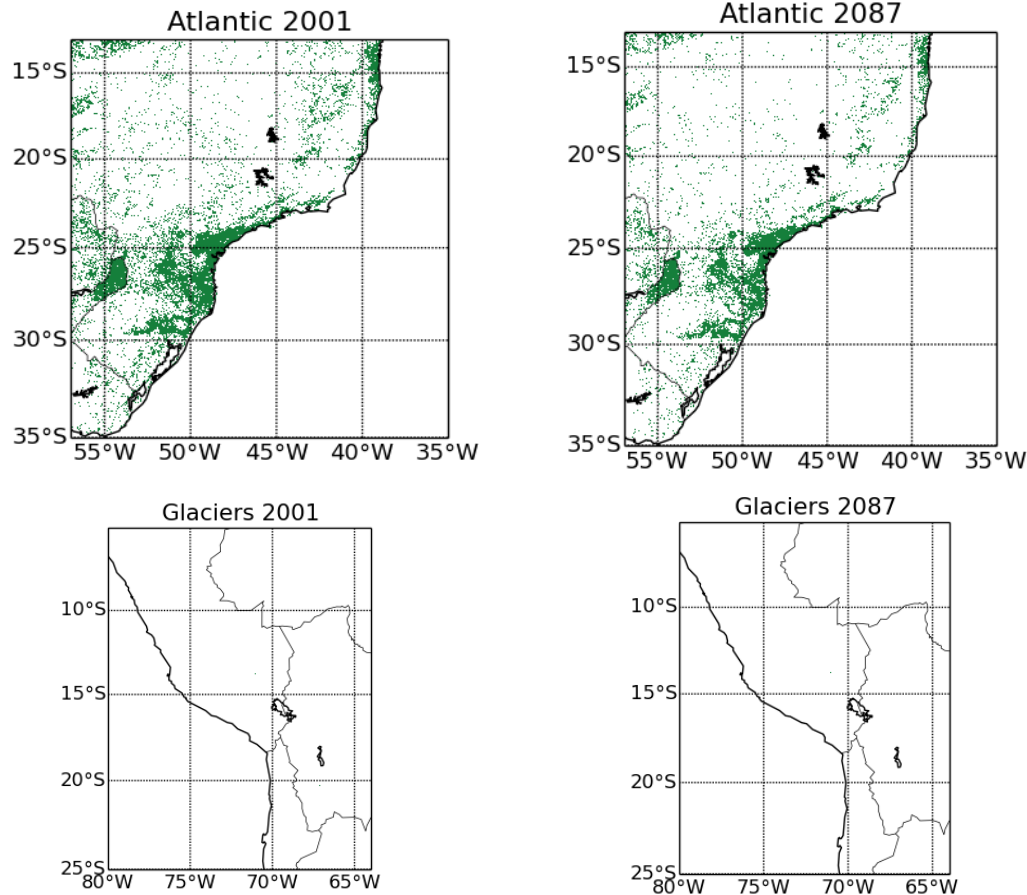
Chaco (CH): Shrink rate assumed to reduce by 2.2% per year versus 2001 levels (Zak et al . 2004)

- Completely gone by 2047

Additional Considerations (2)

Biospheric Changes

Biospheric Regions



Atlantic Forest (AF): Shrink rate 0.343% per year relative to 2001 – Ribel et al. (2009)

- 29.50% reduction by 2087

Tropical Glaciers (TG): Shrink rate 0.6785% per year relative to reference year -- Slayback and Yegar (2006)

- 58.35% reduction by 2087

Additional Considerations (3)

Climate scenarios

Regional climate pathways (RCP):

- RCP 3.0, RCP 4.5, RCP 6.0, RCP 8.5
- Numbers denote change in top of atmosphere radiative forcing in year 2100
- Run as part of the 5th Coupled Modelling Inter-comparison Project (CMIP5)

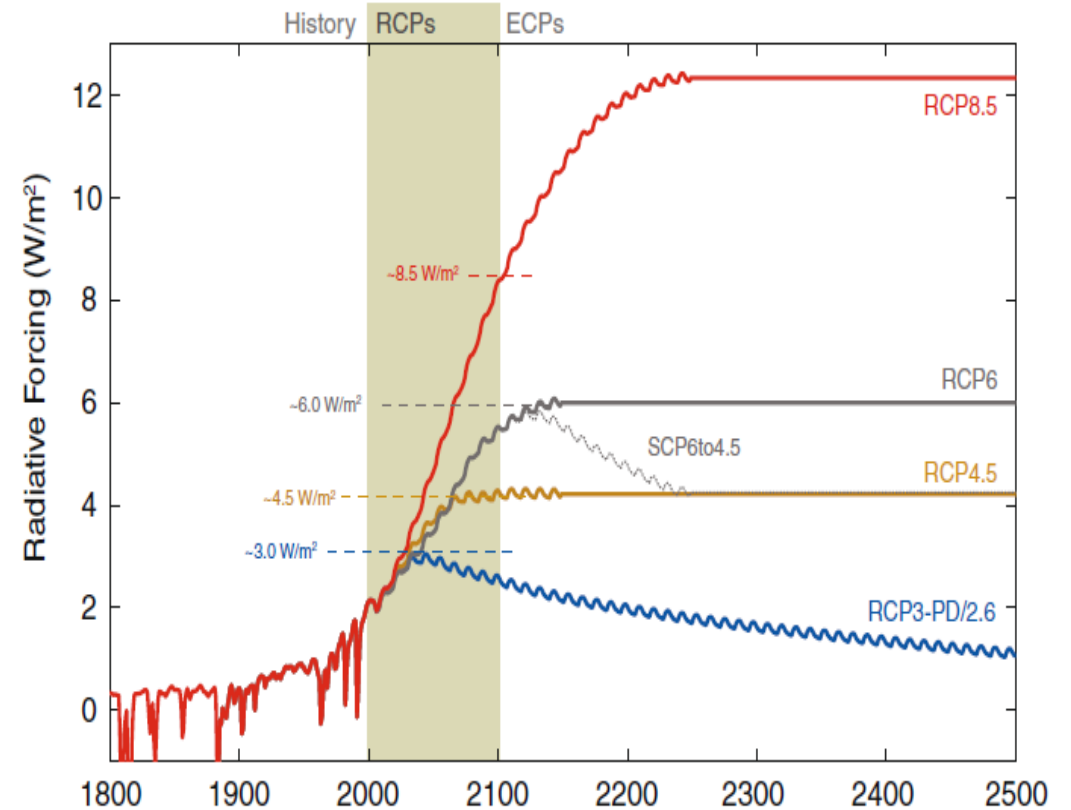
CMIP5 scenarios

- MIROC5 (Japan) – Low sensitivity and good handling of Monsoon circulations (2.8K for 2X CO₂)
- GFDL-ESM2M (GFDL) – Known as one of the most sensitive climate models
- CCSM4 (NCAR) – Known for lower model sensitivity (2.3K for 2X CO₂) – Currently running!!!!

Ran comparison of year long model simulations in the year 2031 to investigate impact of RCP scenario upon COAWST-simulated precipitation

- More on this later!!!!

Before we can discuss the future, how well does COAWST simulate the recent past?



Total radiative forcing (W m⁻²) for four RCP scenarios as adapted from Figure 4 of Meinshausen et al. 2011

Recent climate (7) – Overall Simulation Error

Change in model error as measured by the moist energy norm (Kim and Jung, 2009) (See equation at bottom)

- Volume, integrated error integral encompassing all wind directions, temperature, pressure, and mixing ratio
- Perfect forecast (ECMWF)

Differences in Energy norm (CMH03 – WMH03)

- Notable, but not statistically significant domain 1
- Statistically significant on domain 2

Overall error higher in COAWST simulations

- Same physics, likely associated with free-running model design
- Reasonable simulation of key features in South American climate despite

$$E_m = \iiint_{\sigma, x, y} \frac{1}{2} \left[u'^2 + v'^2 + w'^2 + \left(\frac{g}{N_r \theta_r} \right)^2 \theta'^2 + \left(\frac{1}{\rho_r c_s} \right)^2 p'^2 + \omega_q \frac{L^2}{c_p T_r} q'^2 \right] dy dx d\sigma$$

